Astrometric Method to Break the Photometric Degeneracy between Binary-source and Planetary Microlensing Perturbations

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ABSTRACT

An extra-solar planet can be detected by microlensing because the planet can perturb the smooth lensing light curve created by the primary lens. However, it was shown by Gaudi that a subset of binary-source events can produce light curves that closely resemble those produced by a significant fraction of planet/star lens systems, causing serious contamination of a sample of suspected planetary systems detected via microlensing. In this paper, we show that if a lensing event is observed astrometrically, one can unambiguously break the photometric degeneracy between binary-source and planetary lensing perturbations. This is possible because while the planet-induced perturbation in the trajectory of the lensed source image centroid shifts points away from the opening of the unperturbed elliptical trajectory, while the perturbation induced by the binary source companion points *always* towards the opening. Therefore, astrometric microlensing observations by using future high-precision interferometers will be important for solid confirmation of microlensing planet detections.

Subject headings: gravitational lensing – planetary systems

1. Introduction

Over the past decade, microlensing has developed into a powerful tool in various aspects of astrophysics besides its original use of searching for Galactic dark matter in the form of massive compact halo objects. One important application is the detection of extra-solar planets (Mao & Paczyński 1991; Gould & Loeb 1992). A planet can be detected by microlensing because the planet can perturb the smooth lensing light curve created by the primary lens. Since typical planet-induced perturbations last only a few hours to days, detecting them requires intensive monitoring of events. Currently, two groups (MPS: Rhie et al. 2000; PLANET: Albrow et al. 2001) are conducting follow-up observations of ongoing events alerted by the survey experiments (MACHO: Alcock et al. 2000; EROS: Lasserre et al. 2000; OGLE: Soszyński et al. 2001; MOA: Bond et al. 2001) to increase the planet detection rate by improving the monitoring frequency and photometric accuracy. Once the perturbation is detected, one can determine the mass ratio and the projected separation of the planet.

However, a mere detection of a short-lived perturbation in the lensing light curve does not guarantee the detection of a planet. This is because similar anomalies can also occur due to totally different physical reasons (Gaudi & Gould 1997; Dominik 1999). One well known type of events that produce light curves closely resembling those produced by more than half of planet/star lens systems are a subset of binary-source events where the source companion has a very low flux ratio to the primary source: planet/binary-source degeneracy (Gaudi 1998). For these events, the perturbation occurs when the lens passes closely to the source companion. Gaudi (1998) showed that the probability for this type of perturbations can be comparable to the detection probability of Jupiter-mass planets. Therefore, unless this degeneracy is broken and the true cause of the perturbation is determined, a sample of suspected planetary systems detected via microlensing will be seriously contaminated.

As a new method of detecting planets via microlensing, Safizadeh, Dalal & Griest (1999) proposed to conduct astrometric follow-up observations of lensing events by using several planned high-precision interferometers such as the *Space Interferometry Mission* [SIM, Unwin, Boden & Shao (1997)] and those to be mounted on the Keck (Colavita et al. 1998) and the VLT (Mariotti et al. 1998). From astrometric microlensing observations by using these interferometers, one can measure the displacements in the source star image center of light with respect to its unlensed position, $\boldsymbol{\delta}$ (Miyamoto & Yoshii 1995; Høg, Novikov & Polnarev 1995). The trajectory of the centroid shifts (astrometric curve) caused by a single point-mass lens is an ellipse (Walker 1995; Jeong, Han & Park 1999). A planet can be detected because it can perturb the elliptical astrometric curve of the single lens event, which is analogous to the perturbation in the light curve. Adding astrometric information to the photomet-

ric light curve greatly helps in determining the planetary mass and projected separation, because the lensing behaviors of photometric and astrometric perturbations are strongly correlated (Safizadeh, Dalal & Griest 1999; Han & Lee 2001).

In this paper, we investigate whether one can break the planet/binary-source degeneracy in lensing light curves from astrometric microlensing observations. In § 2, we briefly describe the basics of microlensing. In § 3, we show that the degeneracy can be unambiguously broken astrometrically by demonstrating the fundamental differences between the astrometric curves resulting from a photometrically degenerate case of binary-source and planetary lensing events. We conclude in § 5.

2. Basics of Microlensing

2.1. Standard events

If a single source located at $\boldsymbol{\theta}_{\rm S}$ on the projected plane is lensed by a coplanar N point-mass lens system, where the individual masses and locations are m_j and $\boldsymbol{\theta}_{{\rm L},j}$, the positions of the resulting images $\boldsymbol{\theta}$ are obtained by solving the lens equation of the form

$$\boldsymbol{\theta}_{\rm S} = \boldsymbol{\theta} - \frac{\theta_{\rm E}^2}{m} \sum_{j=1}^{N} m_j \frac{\boldsymbol{\theta} - \boldsymbol{\theta}_{{\rm L},j}}{|\boldsymbol{\theta} - \boldsymbol{\theta}_{{\rm L},j}|^2}, \tag{1}$$

where $m = \sum_{j=1}^{N} m_j$ is the total mass of the lens system and $\theta_{\rm E}$ is the angular Einstein ring radius. The Einstein ring radius is related to the physical parameters of the lens system by

$$\theta_{\rm E} = \sqrt{\frac{4Gm}{c^2}} \left(\frac{1}{D_{\rm ol}} - \frac{1}{D_{\rm os}} \right)^{1/2}, \tag{2}$$

where $D_{\rm ol}$ and $D_{\rm os}$ are the distances to the lens and source from the observer, respectively. The lensing process conserves the surface brightness, and thus the magnification of the source star flux equals the ratio of the surface areas between the image and the unlensed source. The magnifications of the individual images are given by the Jacobian of the transformation (1) evaluated at the image position, i.e.

$$A_i = \left(\frac{1}{|\det J|} \right)_{\boldsymbol{\theta}=\boldsymbol{\theta}_i}; \qquad \det J = \left| \frac{\partial \boldsymbol{\theta}_{\rm S}}{\partial \boldsymbol{\theta}} \right|. \tag{3}$$

Then, the total magnification and the centroid shift vector are obtained respectively by $A = \sum_{i=1}^{N_I} A_i$ and $\boldsymbol{\delta} = \sum_{i}^{N_I} A_i \boldsymbol{\theta}_i / A - \boldsymbol{\theta}_{\rm S}$, where N_I is the total number of images.

When a single source is lensed by a single point-mass lens (standard event), the lens equation is easily solvable and yields two solutions. The resulting images appear at the positions

$$\boldsymbol{\theta}_{\pm} = \frac{\theta_{\rm E}}{2} \left[u \pm (u^2+4)^{1/2} \right] \frac{\boldsymbol{u}}{u}, \tag{4}$$

and have amplifications

$$A_{\pm} = \frac{1}{2} \left[\frac{u^2+2}{u(u^2+4)^{1/2}} \pm 1 \right], \tag{5}$$

where $\boldsymbol{u} = (\boldsymbol{\theta}_{\rm S} - \boldsymbol{\theta}_{\rm L})/\theta_{\rm E}$ is the dimensionless lens-source separation vector normalized by $\theta_{\rm E}$. The separation vector is related to the single lensing parameters by

$$\boldsymbol{u} = \left(\frac{t-t_0}{t_{\rm E}} \right) \hat{\boldsymbol{x}} \pm \beta \, \hat{\boldsymbol{y}}, \tag{6}$$

where $t_{\rm E}$ is the Einstein ring radius crossing time (Einstein time scale), β is the closest lens-source separation (impact parameter)[1], t_0 is the time at the moment of the closest approach, and the unit vectors $\hat{\boldsymbol{x}}$ and $\hat{\boldsymbol{y}}$ are parallel with and normal to the direction of the relative lens-source transverse motion, respectively. Then, the brighter image (major image), denoted by the subscript '+', is located outside of the Einstein ring and the other fainter image (minor image), denoted by the subscript '−', is located inside of the ring along the line connecting the lens and the source. The two images formed by the lens cannot be resolved, but one can measure the total magnification and the shift of the source image centroid with respect to its unlensed position, which are represented respectively by

$$A = A_+ + A_- = \frac{u^2+2}{u\sqrt{u^2+4}}. \tag{7}$$

and

$$\boldsymbol{\delta} = \frac{A_+ \boldsymbol{\theta}_+ + A_- \boldsymbol{\theta}_-}{A} - \boldsymbol{u} = \frac{\boldsymbol{u}}{u^2+2} \, \theta_{\rm E}. \tag{8}$$

The light curve of a standard event has a smooth and symmetric shape, where its height (peak magnification) and width (duration) are determined respectively by β and $t_{\rm E}$. The centroid shift traces an elliptical trajectory with a semi-major axis $a = \theta_{\rm E}/2(\beta^2+2)$ and an eccentricity $\varepsilon = [(\beta^2/2)+1]^{-1/2}$ (Jeong, Han & Park 1999).

2.2. Planetary Microlensing Events

The lens system with a planet is described by the formalism of the binary lens system with a very low mass companion. For this case, the lens equation can be represented as a fifth degree polynomial (Witt & Mao 1995) and numerical solution of the equation yields three or five solutions depending on the source position with respect to the lenses.

The main new features of binary lenses relative to single point-mass lenses are caustics. These are the closed curves on the source plane where a point source is infinitely magnified. Hence, significant deviations both in the light and astrometric curves occur when the source

[1] Note that the sign '±' in front of β in eq. (6) is used because β is positive definitive.

passes the region close to the caustics. The size of the caustics, and thus the planet detection probability, depends both on the mass ratio, q, and the projected separation (normalized by $\theta_{\rm E}$), b, between the planet and the primary lens. The caustic size decreases with the decreasing value of $\sqrt{q}$, and thus planet-induced perturbations last only a short period of time. For a given mass ratio, the caustic size is maximized when the projected star-planet separation is in the range $0.6 \lesssim b \lesssim 1.6$, the 'lensing zone'.

There are two types of planetary perturbations: those which perturb the major image of the source formed by the primary lens, and those which perturb the minor image (Gould & Loeb 1992). Photometrically, major image perturbations are characterized by positive deviations from the single lensing light curve, while minor image perturbations are characterized by negative deviations (Gaudi 1998).

2.3. Binary-Source Events

Unlike the non-linear behavior of binary-lens events, binary-source lensing is simple because the lensing behavior involved with each source can be treated as an independent single source event (Griest & Hu 1992). Then the light and astrometric curves of a binary-source event are represented by

$$A = \frac{A_1 + \mathcal{R} A_2}{1+\mathcal{R}}, \tag{9}$$

and

$$\boldsymbol{\delta} = \frac{A_1(\boldsymbol{u}_1 + \boldsymbol{\delta}_1) + \mathcal{R} A_2(\boldsymbol{u}_2 + \boldsymbol{\delta}_2)}{A_1 + \mathcal{R} A_2} - \frac{\boldsymbol{u}_1 + \mathcal{R}\boldsymbol{u}_2}{1+\mathcal{R}}, \tag{10}$$

where $\boldsymbol{u}_i$ are the separation vectors between the lens and the individual source components, $\mathcal{R}$ is their (unlensed) flux ratio, $A_i = (u_i^2+2)/u_i(u_i^2+4)^{1/2}$ and $\boldsymbol{\delta}_i = \boldsymbol{u}_i\theta_{\rm E}/(u_i^2+2)$ are the magnifications and centroid shifts of the individual single source events (denoted by the subscripts $i = 1$ and 2) (Han 2001). We note that the reference position of the centroid shift measurements for the binary-source event is the center of light between the unlensed source components, i.e, the second term in eq. (10).

3. Planet/Binary-source Degeneracy

If the sources of a binary-source event have a small flux ratio and the fainter source passes close to the lens, the resulting light curve can mimic that of a planetary lensing event. The perturbation produced by the binary source companion is always positive, and thus it imitates major image perturbations, which comprises majority of planet-induced perturbations. In Figure 1, we illustrate this degeneracy by presenting the light curves (lower left panel) resulting from an example case of binary-source (solid curve) and planetary lensing (dotted curve) events suffering from the degeneracy. In the upper panels, we also present the lens system geometries of the events. We note that while the geometry of the binary-source event is represented with respect to the sources, the geometry of the planetary lensing event is represented with respect to the lenses. For the binary-source event, the flux ratio and the separation between the sources are $\mathcal{R} = 5\times10^{-3}$ and $b = 0.5$, respectively. For the planetary lensing event, the mass ratio and the separation between the lenses are $q = 10^{-3}$ and $b = 1.183$, respectively. We note that the light curves are identical to those presented in Fig. 1 of Gaudi (1998).

To mimic the light curve of a planetary lensing event, a binary-source event should satisfy the specific requirements of the small flux ratio and the close passage of the lens to the fainter source. Gaudi (1998) estimated the probabilities to satisfy these requirements and found that for binary sources with separations of $0.5 \lesssim b \lesssim 1.5$ the probabilities range from a few percent to ~ 30 percent for binaries with magnitude differences of $\Delta V \sim 4-7$. These probabilities are of the same order of magnitude as the probabilities of detecting anomalies induced by Earth-mass to Jupiter-mass planets located in the lensing zone (Gould & Loeb 1992; Bennett & Rhie 1996; Peale 2001). Therefore, binary sources can seriously contaminate a sample of planet candidates detected by microlensing.

Gaudi (1998) discussed several methods to break the degeneracy. These include accurate and dense photometric sampling and multi-band (optical/infrared) photometric measurements of color changes (or spectroscopic measurements of the variation in spectrum) during perturbations. The first method utilizes the differences in the detailed lensing light curves between the two degenerate cases of events. However, applying this method is significantly limited because the differences are, in general, very small and even noticeable differences last a very short period of time. The other method utilizes the differences in the behaviors of color or spectral changes occurred during the perturbations. However, this method also has significant limitations because the expected color or spectral changes are very small.

However, if events are monitored from astrometric follow-up observations, the planet/binary-source degeneracy can be unambiguously broken due to the fundamental differences between the astrometric lensing behaviors of binary-source and planetary lensing events. To demonstrate this, in the lower right panel of Figure 1, we present the astrometric curves resulting from the photometrically degenerate case of binary-source (solid curve) and planetary lensing (dotted curve) events whose light curves are presented in the lower left panel. One finds that while the planet-induced perturbation points away from the opening of the unperturbed astrometric curve (outward perturbation), the perturbation induced by the binary source companion points towards the opening (inward perturbation). These trends of astrometric

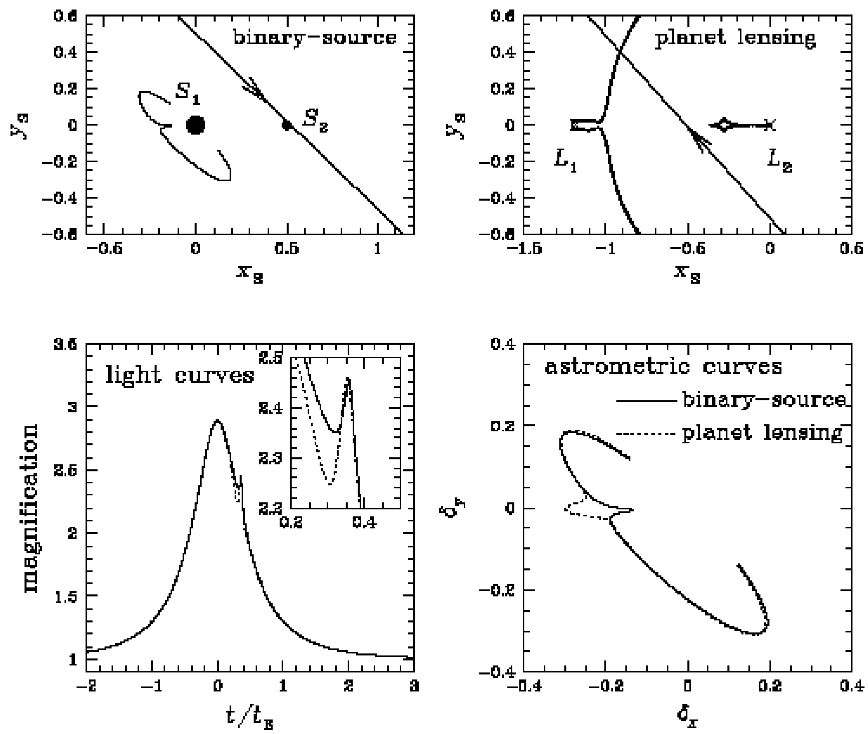

Fig. 1.— The light (lower left panel) and astrometric curves (lower right panel) resulting from an example case of binary-source and planet microlensing events suffering from the photometric planet/binary-source degeneracy. The upper panels show the lens system geometries of the binary-source (upper left panel) and the planetary lensing events (upper right panel). The geometry of the binary-source event is represented with respect to the sources, denoted by S_1 (brighter source) and S_2 (fainter source), and the straight line with an arrow represents the lens trajectory. On the other hand, the geometry of the planetary lensing event is represented with respect to lenses, denoted by L_1 (primary lens) and L_2 (planet), and the straight lines with an arrow represents the source trajectory. The astrometric curve of the binary-source event is additionally presented in the upper left to show the centroid motion with respect to the source positions. The curves in the upper right panel are the caustics (diamond shaped figure) and the critical curve of the planet lens system.

perturbations for the binary-source and planetary lensing events are not specified only for the presented example events, but are generic properties of these types of events. From the investigation of of the properties of planet-induced astrometric perturbations, Han & Lee (2001) found that both cases of the planet's perturbations of major and minor images result in the same outward astrometric deviations.[2] The characteristic inward astrometric perturbations of binary-source events occur due to the specific geometry of the lens systems. This can be seen in the upper left panel of Fig. 1, where we additionally plot the astrometric curve of the binary-source event to see the source image centroid motion with respect to the source positions. When the lens is away from the source companion, the motion is well described by that of the event with the single brighter source and the centroid follows an elliptical trajectory. During this time, the image centroid is located on the opposite side of the lens with respect to the unlensed position of the brighter source. When the lens approaches the source companion, on the other hand, the companion is highly amplified and the centroid motion is perturbed. Since the lens is close to the companion, this perturbation is directed towards the lens, which is opposite direction compared to the centroid location without the companion. Therefore, binary-source events producing light curves resembling those produced by planetary lens system *always* result in astrometric curves with inward perturbations.

[2]For more examples of planet-induced astrometric perturbations, see Fig. 5 (for major image perturbations) and Fig. 7 (for major image perturbations) of Han & Lee (2001).

4. Conclusion

We have shown that with additional information from astrometric lensing observations one can unambiguously break the photometric degeneracy between binary-source and planetary lensing perturbations. This is possible because binary-source events producing light curves imitating those of planetary lensing events result in astrometric perturbations pointing towards the opening of the unperturbed astrometric curves, while astrometric perturbations induced by planets point away from the opening. Therefore, astrometric lensing observations by using future high precision interferometers will be important for solid confirmation of planet detections.

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